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Competition and Innovation: An Experimental Investigation*

Donja Darai, Dario Sacco and Armin Schmutzler*

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Abstract: The paper analyzes the effects of more intense competition on firms' incentives to invest in process innovations. We carry out experiments for two-stage games, where R&D investment choices are followed by product market competition. As predicted by theory, an increase in the number of firms from two to four reduces investments. However, a positive effect is observed for a switch from Cournot to Bertrand, even though theory predicts a negative effect in the four-player case. This result reflects overinvestment in the Bertrand case. The results arise both in treatments in which both stages are implemented and in treatments in which only one stage is implemented.

JEL Classification: C92, L13, O31.

Keywords: R&D investment, intensity of competition, experiment.

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1 Introduction

Simple two-stage games are often used to derive predictions about the effects of increasing competition on cost-reducing investments.[1] The empirical test of these predictions is very difficult, and the literature comes to ambiguous conclusions.[2] Therefore, this paper uses laboratory experiments as a complementary research approach to explore whether at least the basic strategic effects identified in the theoretical models are present in a laboratory setting.

Specifically, we consider four different games where two or four firms can choose a cost-reducing investment before they engage in Cournot or Bertrand competition with homogeneous goods. In this fashion, we can explore the effects of increasing competition both by increasing the number of players and by switching from Cournot to Bertrand competition. Thus, we can capture two of the most familiar notions of increasing competition.

The predicted effect of competition on investment is unambiguously negative for an increase in the number of firms. For a shift from Cournot to Bertrand competition, the effect is always negative for three firms or more. In the duopoly case, the effect is positive except for very small investment costs.

The experiments fully confirm the negative number effects.[3] For a switch from Cournot to Bertrand competition, however, the observed effect is always positive, even when the predicted effect is negative. This observation relates to how players deviate from the Nash equilibrium. Whereas investments are close to the equilibrium in the Cournot case, there is substantial overinvestment in the Bertrand case. This overinvestment reinforces the predicted positive effect in the two-player case, and it turns the predicted negative effect into a positive effect for the four-player case.

To understand better what drives the results and, in particular, what lies behind the overinvestment in the Bertrand case, we made an important design decision. We not only considered treatments with the two-stage structure of the underlying game, but we also considered one-stage treatments where subjects' investment decisions automatically result in the payoffs of the ensuing product-market subgame. This design feature allows us to inves-

[1] Schmutzler (2007) and Vives (2008) synthesize the existing literature.

[2] See Gilbert (2006) and Section 2.2 below.

[3] Importantly, note that our analysis is distinct from the more familiar analysis of number effects in oligopolies (Huck et al. 2004; Orzen 2008). This literature deals with the effects on prices and quantities rather than on investments.

tigate whether deviations from the equilibrium investments in the two-stage game are driven exclusively by expected deviations in the product-market game. As it turns out that the main comparative-statics results arise both in the one-stage and two-stage treatments, it is unlikely that such expected second-stage deviations are exclusively responsible for the investment behavior.

Obviously, a simple set of experiments cannot resolve the century-old debate about the effects of competition on investment. First of all, there are too many conceptual ambiguities at the theoretical level. Even the definition of increasing intensity of competition is contentious, some insightful attempts to structure the debate notwithstanding.[4] Second, even if one settles for a specific notion of increasing competition in two-stage games, there is a bewildering variety of models to investigate the issue.[5] Third, of course, one can go beyond the two-stage setting and investigate more complicated dynamic models.[6] Finally, one may worry about the external validity of the laboratory setting as a means of testing predictions about the long-term strategic decisions of managers in (potentially large) firms.

In spite of all these cautionary remarks, we believe that the subsequent analysis leads to one important insight: Our laboratory analysis suggests that behavioral effects may imply a more positive effect of competition on investment than a purely theoretic analysis would reveal.[7] Future work will have to show how robust these effects are in the lab. More importantly, perhaps, it will have to show whether the effect is also present in the field.

The paper is structured as follows. Section 2 summarizes related literature

[4]Boone (2000) shows that many different measures of competition share the common property that increasing competition can be associated with a higher ratio of the profits between more efficient and less efficient firms.

[5]Vives (2008) provides a unifying discussion of two-stage games, with the extent of product differentiation as an inverse measure of competition. Schmutzler (2007) extends the discussion to other measures of competition.

[6]For instance, Lee and Wilde (1980) identify a positive effect of the number of firms on investment per firm in a Bertrand setting, whereas Delbono and Denicolò (1991) find a negative effect, even on total investment, in the Cournot case. In a stochastic patent race preceding product market competition, Delbono and Denicolò (1990) show that investment in the Bertrand case is unambiguously higher than in the Cournot case. Bester and Petrakis (1993) show that, with sufficiently large horizontal product differentiation, the innovation incentive is higher under Cournot competition than under Bertrand competition.

[7]Note that "positive" is not supposed to have any welfare interpretation here. In fact, increasing competition may well induce excessive investment from a welfare perspective.

and Section 3 contains the theoretical framework. Section 4-6 describes the experimental design and results. Section 7 concludes.

2 Related Literature

2.1 Experimental Literature

2.1.1 Existing papers

Some of the ingredients of our approach are familiar from other sources. For instance, Suetens (2005) considers investment games in a Cournot setting. She focuses on the differences between investments and the Nash equilibrium, and specifically on the role of knowledge spillovers in this context. The effects of increasing competition are not a matter of concern. Isaac and Reynolds (1988, 1992) consider the number effects. They deal with stochastic static and dynamic patent races, and they show that an increase in the group size lowers investment per firm and raises aggregate investment. Sacco and Schmutzler (2009) also analyze Cournot investment games, but they are concerned with the effects of increasing competition by changing the degree of competition in a differentiated product market. They expose a U-shaped relation in the underlying Shubik-Levitan model, and they provide weak experimental evidence in favor of such a relation.

Sacco and Schmutzler (2008) consider the reduced one-stage version of a two-stage Bertrand game, where investments precede price competition. They show that overinvestment is substantial. However, there, they also do not deal with the effects of increasing competition.[8] More broadly, our Bertrand investment experiments are related to the literature on all-pay auctions: Even when all players invest a positive amount, only one player can make positive profits. However, contrary to standard all-pay auctions, the size of the bids affects not only the chances of winning, but also the prize. In particular, at least in the one-stage version, when the difference to the second-highest bid is close to zero, so is the winner's prize. In spite of these differences in the strategic setting, our experimental observations are similar to those that are familiar from the fixed-prize all-pay auctions. Most closely related is Gneezy and Smorodinsky (2006) who consider symmetric all-pay

[8] The theoretical part of the paper deals more generally with all-pay auctions with negative prize externalities. The Bertrand investment game used in the experiment is a special case of the general set-up.

auctions with 4, 8, and 12 players and also observe overinvestment. Like us, these authors obtain overbidding that diminishes over time, but remains substantial even in later periods.[9] Summing up, even though the equilibrium structure of the one-stage Bertrand investment game differs substantially from the fixed-prize case, the experimental observations, in particular, the overbidding phenomenon, are quite similar.

2.1.2 Our contribution

Our approach differs from the existing literature in several important ways.

First, we are not aware of any study that uses a simple unified framework that analyzes the effects of increasing competition both in the sense of increasing the number of firms and of moving from Cournot to Bertrand competition. Existing work on investment games has focused exclusively on Cournot competition or on non-standard models, and it is not directly comparable. Also, the existing individual contributions are cast in different frameworks, making them hard to compare. Whereas Suetens (2005) considers a standard Cournot framework like us, Isaac and Reynolds (1988, 1992) deal with stochastic static and dynamic patent races. We are also not aware of experimental papers comparing Cournot to Bertrand competition.

Second, our paper appears to be the first one that explicitly juxtaposes the two-stage and one-stage treatments so as to obtain a better understanding of deviations from equilibrium in the two-stage game. For instance, this distinguishes our approach from Suetens (2005) who exclusively focuses on the two-stage setting, whereas we compare the two-stage and the one-stage setting.

Third, our analysis suggests one empirical insight that does not follow from existing papers. It appears that an increase in competition in the sense of a move from Cournot to Bertrand competition is more likely to have a positive effect on investments than theory would suggest.

[9] Other broadly related papers are Davis and Reilly (1998), Millner and Pratt (1989) and Shogren and Baik (1991). However, unlike us, the last two papers focus on probabilistic all-pay auctions where higher bids increase the chances of winning, but do not guarantee it.

2.2 Field evidence

We see our research as complementary to the existing empirical work, which comes to ambiguous conclusions about the effects of competition on investment. The early literature, surveyed in Cohen and Levin (1989), regarded market structure as an explanatory variable.[10] However, the causality might run in the opposite direction. Innovation may affect market structure because R&D involves fixed costs or because it affects the pattern of firm growth in an industry. Innovation can also affect market structure indirectly, by increasing or decreasing the efficient scale of production. This endogeneity problem has been taken into account to some extent by the more recent literature. This literature nevertheless does not come to unambiguous conclusions. For instance, Nickell (1996) obtains a positive effect of competition on investments. In Aghion et al. (2005), an inverted-U relationship between intensity of competition and investments arises. The ambiguity in the empirical literature may reflect the fact that details in the underlying situation may affect the relation between competition and investment. An experimental analysis addresses both problems: It allows us to delineate a setting in which the theoretical predictions are clear and there are no endogeneity problems.

3 The Model

We analyze static two-stage games, where firms $i = 1, ..., I$ first invest in R&D and then compete in the product market. The demand function for the homogeneous product is given by $D(p) = a - p$, with $a > 0$. All firms i are identical ex-ante, with constant marginal costs $c > 0$. In the first stage, firms simultaneously choose R&D investments $Y_i \in [0, c)$, resulting in marginal costs $c_i = c - Y_i$. The cost of R&D is given by kY_i^2, where $k > 0$. In the second stage, firms simultaneously choose quantities (Cournot competition) or prices (Bertrand competition).

[10] For an introduction to more recent evidence, see Gilbert (2006).

3.1 Cournot Competition

For the Cournot case, backward induction shows that the net payoff function of firm i in the first stage is given by

$$\Pi_i(Y_1, ..., Y_I, \alpha, k) = \left(\frac{\alpha + IY_i - \sum_{i \neq j} Y_j}{I+1}\right)^2 - kY_i^2, \tag{1}$$

where $\alpha \equiv a - c$ represents the demand parameter.[11]

The gross payoff of firm i, that is, the first term on the right-hand side of (1), depends positively on its own investment and the demand parameter, and negatively on the investments of the other firms.

Maximizing (1) with respect to Y_i yields

$$\frac{\partial \Pi_i(\cdot)}{\partial Y_i} = \frac{2I(\alpha + IY_i - \sum_{i \neq j} Y_j)}{(I+1)^2} - 2kY_i \equiv 0. \tag{2}$$

This immediately yields the following result[12]:

Proposition 1 *Under Cournot competition the symmetric pure-strategy Nash equilibrium investment levels are*

$$Y^C = \frac{\alpha I}{k(I+1)^2 - I}. \tag{3}$$

By (3), equilibrium investments are increasing in the demand parameter α, and decreasing in the cost parameter k and in the number of firms I.

3.2 Bertrand Competition

For Bertrand Competition, backward induction shows that the net payoff function of firm i can be written as a function of efficiency levels as follows:

$$\Pi_i(\cdot) = \begin{cases} (Y_i - Y_{-i}^m)D(c - Y_{-i}^m) - kY_i^2, & \text{if } Y_i > Y_{-i}^m \\ -kY_i^2, & \text{if } Y_i \leq Y_{-i}^m \end{cases}, \tag{4}$$

where $Y_{-i}^m = \max_{j \neq i} Y_j$. Compared to the Cournot case, competition is intense in the sense that a firm can achieve a positive gross payoff only by

[11] Here and in the following, we assume that $\alpha + IY_i - \sum_{i \neq j} Y_j \geq 0$.

[12] We assume that the second order condition holds, that is, $I^2/(I+1)^2 - k < 0$, which is fulfilled for arbitrary $I \geq 2$ if $k > 1$.

investing more than the highest investment of the others. If $Y_i > Y_{-i}^m$, maximizing (4) with respect to Y_i gives

$$\frac{\partial \Pi_i(\cdot)}{\partial Y_i} = D(c - Y_{-i}^m) - 2kY_i \equiv 0. \tag{5}$$

$Y_i \leq Y_{-i}^m$ can only be a best response if $Y_i = 0$ holds: If firm i does not invest more than all others, it gets a negative net payoff. In such a case the deviation to $Y_i = 0$ is profitable. The pure-strategy equilibrium is thus characterized as follows.

Proposition 2 *(i) Under Bertrand Competition, for $k > \frac{1}{2}$, there are multiple asymmetric pure-strategy equilibria with one firm investing $Y_i^B = \frac{\alpha}{2k}$ and firms $j \neq i$ investing $Y_j^B = 0$. (ii) There are no other pure-strategy equilibria.*

For the simple proof, we refer the reader to Sacco and Schmutzler (2008, Prop. 7).

Proposition 2 implies that the average equilibrium investment level is given by

$$\overline{Y}^B = \frac{\alpha}{2kI}, \tag{6}$$

which is increasing in the demand parameter, and decreasing in the cost parameter k and in the number of firms I.

It is unlikely that agents can coordinate on one of the asymmetric pure-strategy equilibria, in particular, because only the investor obtains positive payoffs. In the experimental analysis, we therefore refer to the following result of Sacco and Schmutzler (2008).

Proposition 3 *The investment game with Bertrand Competition has a symmetric mixed-strategy equilibrium, where firms mix between all strategies up to a cut-off level.*[13]

Of course, one may be concerned with the relevance of mixed-strategy equilibria in the context of an oligopoly with a small number of players. We clearly do not expect decision makers in firms to randomize deliberately.

[13] The game also has asymmetric mixed-strategy equilibria where some firms always play zero and others randomize.

Also, the common justification that mixed-strategy equilibria describe behavior in large populations of players, each of which takes non-random decisions, makes no sense in our context. A more convincing a priori justification relies on standard purification arguments (Harsanyi 1973).[14]

3.3 The Effects of Increasing Competition

We now consider the predicted effects of competition on investment.

Corollary 1 *The average equilibrium investments are decreasing in I for both Bertrand and Cournot competition.*

Similarly, comparing (3) to (6), the following result arises.

Corollary 2 *Suppose that $k > \max\left\{\frac{1}{2}, \frac{I^2}{(I+1)^2}\right\}$. The average equilibrium investment for Cournot is higher than the average investment in each asymmetric pure-strategy equilibrium for Bertrand for $I \geq 3$. For $I = 2$, average investments are higher for Bertrand unless $k \leq 2$.*

Though we cannot provide such results for the mixed-strategy equilibrium at this level of generality, a similar statement holds for the parameters we choose (see 4.2). Thus, except for the caveat for $I = 2$, for both concepts of competitiveness, an increase in competition reduces investment.

Both of these changes in the competitive environment have the common feature that they correspond to reductions in the mark-ups that firms can command in the product market. To see the crucial difference, note that an increase in the number of competitors in a Cournot setting has a fairly smooth effect on the nature of competition. Most importantly, both firms can obtain positive profits before and after the change in competition. As one moves from Cournot to Bertrand, the change in the competitive environment is more dramatic: It is well known that at most one firm can obtain a positive profit in the Bertrand investment game when both firms choose equilibrium prices in the ensuing subgame; so that competition is of a winner-takes-all nature. Thus, without correct expectations about competitor investments

[14]Specifically, one can consider a Bayesian game with a continuum of players with statistically independent types, reflecting small differences in payoffs. The mixed-strategy equilibrium of the complete information game is then close to the equilibria of nearby Bayesian games.

players may easily take very bad decisions. This strategic complexity is reflected in the equilibrium structure. While the Cournot investment game has a unique symmetric pure-strategy equilibrium, the Bertrand game has multiple asymmetric pure-strategy equilibria, a symmetric mixed-strategy equilibrium and even asymmetric mixed-strategy equilibria. Therefore, it is not all obvious how players coordinate in a static setting. Perhaps the most plausible equilibrium candidate is the symmetric mixed-strategy equilibrium. We use this benchmark to predict equilibrium investments in the Bertrand game, whereas we resort to the symmetric pure-strategy equilibrium in the Cournot case.

4 Experimental Design

4.1 Treatments

We conducted eight treatments (see Table 1), which differed in the following three dimensions:

1. The number of players (two vs. four)
2. The mode of competition (Bertrand vs. Cournot)
3. The number of stages played out (one vs. two)

	Type of competition	
Number of players	Bertrand	Cournot
$I = 2$	B2, 2 sessions	C2, 2 sessions
$I = 4$	B4, 2 sessions	C4, 2 sessions

Note, for each treatment we ran one session with one stage and one with two stages played out. The two (four) player sessions consist each of 36 (32) subjects grouped into nine (four) matching groups.

Table 1: Treatments

The need for the first two treatment variations is obvious given our questions of interest. The third point requires some clarification. Clearly, to capture the models introduced in Section 3 accurately, the two-stage treatments are adequate. Unfortunately, in such treatments, there may be confusion about the source of possible deviations from the equilibrium in the investment game. Broadly, one can imagine two classes of deviations. First, subjects may be expecting non-equilibrium behavior in the product market stage.[15] For instance, they might expect that all parties (including themselves) collude below the equilibrium output in the Cournot game, in which case they should rationally choose lower than equilibrium investments in the first stage. Second, even when they do not expect such deviations in the product market game, players may want to deviate from equilibrium investments for other reasons. For instance, they might realize that investments involve negative externalities, and they may want to coordinate on lower investments that make both players better off than equilibrium investments would.

To be able to identify which of these two types of deviations are relevant, we conducted all treatments in two different ways. Like Halbheer et al. (forthcoming), we considered one-stage treatments, in which players only choose investment levels, and we assumed that payoffs for each choice of investments correspond to the payoffs in the equilibrium of the ensuing product market game. In these treatments, deviations from equilibrium cannot result from expected deviations in the product market game, because behavior in this game corresponds to equilibrium values. In addition, we considered two-stage treatments in which players had to play the product market game as well. Thus, we can identify to which extent deviations in the two-stage game are attributable to each source of deviations.

4.2 Parameters and Predictions

We chose parameter values $\alpha = 30$ and $k = 3$. In the experiments, we restricted the strategy sets to $Y_i \in \{0, 1, ..., 9\}$. Restricting choices to discrete strategies had two main advantages. First, we could present information on payoffs (gross of investment costs) in simple matrices. Second, in this fashion, the integers no longer play the role of prominent numbers. The downside is that the equilibria of the game with the discrete strategy set are $(2, 2)$ for the two-player Cournot game and $(2, 2, 2, 2)$ for the four-player game, so that a change in the number of players has no effect on predicted per-player investments. However, this comparative-statics prediction of zero effects relies on an extremely mechanical application of the Nash equilibrium. As many

[15] Such deviations are known to arise both in the Bertrand case (Dufwenberg and Gneezy, 2000) and in the the Cournot case (Huck et al. 2004, and many others).

experiments have shown, comparative-statics predictions of discrete games are problematic. Often parameter changes in such games do not affect the equilibrium, even though economic intuition strongly suggests that behavior should change.[16] It appears likely that this standard problem of comparative-statics predictions in discrete games arises in our model as well. Intuitively, marginal investment incentives, given by the derivative of gross profits with respect to efficiency levels, are higher for each player in the Cournot game with two players than with four players.[17] Economic intuition therefore suggests that the effect of increasing the number of players should be negative rather than zero as the comparison of the equilibria of the discrete games would predict.[18] The simplest way to obtain this negative effect is by viewing the players as playing a continuous game: In the Nash equilibrium of the continuous version of the two-player game, investments are higher than for the four-player game ($2.4 > 1.69$). We find this prediction much more convincing than the prediction that the equilibrium is unaffected by a change in the number of players. Even when each player can only choose discrete investment levels, the average behavior can well be continuous.

For Bertrand competition, according to Proposition 2, there are asymmetric equilibria, each with one firm investing 5 and the other firm(s) 0. This holds both for the discrete and continuous strategy set. Moreover, according to Sacco and Schmutzler (2008)[19], the two-player game has a symmetric mixed-strategy equilibrium (MSE) given by

$$(p_0, ..., p_9) = (0.1, 0.193, 0.187, 0.182, 0.176, 0.160, 0, 0, 0, 0)\,. \tag{7}$$

For the four-player game, the symmetric MSE is given by

$$(p_0, ..., p_9) = (0.464, 0.2, 0.119, 0.088, 0.071, 0.057, 0, 0, 0, 0)\,. \tag{8}$$

[16] For instance, some of the examples in Goeree and Holt (2001) have this property, in particular, the two proposal games (Goeree and Holt (2001), p.1411-1412), in which the responder's payoffs are modified strongly, but without affecting his best response. The observed behavior changes massively.

[17] For instance, in a symmetric situation where efficiency levels are Y for all players, the respective derivatives are $\frac{4}{9}(30 + Y)$ in the two-player case and $\frac{8}{25}(30 + Y)$ in the four-player case.

[18] Schmutzler (2007) formalizes this intuition. He gives general conditions under which an increase in the number of players (weakly) reduces the investments of players in an investment game. These conditions hold in the example.

[19] Sacco and Schmutzler (2008) provide an algorithm for calculating the equilibria.

The expected investment level is 2.62 for the two-player and 1.27 for the four-player Bertrand game. Note that the expected investment levels are close to the average investments ($\overline{Y}^{B2} = 2.5$; $\overline{Y}^{B4} = 1.25$). As long as one is only concerned with average behavior, the difference between the different types of equilibria is thus marginal.

The following Table provides an overview of the predicted equilibrium investments:

Model	Equilibrium investment		
	discrete	continuous	mixed
Cournot $I = 2$	(2, 2)	(2.4, 2.4)	-
Cournot $I = 4$	(2, 2, 2, 2)	(1.69, 1.69, 1.69, 1.69)	-
Bertrand $I = 2$	(5, 0)	(5, 0)	(2.62, 2.62)
Bertrand $I = 4$	(5, 0, 0, 0)	(5, 0, 0, 0)	(1.27, 1.27, 1.27, 1.27)

Note, the mixed equilibria are expected investment levels, see equations (7) and (8)

Table 2: Equilibria

With the equilibria we derive four hypotheses about the effects of increasing competition.

Hypothesis 1a *In the Cournot case, increasing competition in the sense of switching from 2 to 4 players reduces investments.*

We repeat that this prediction is based on the equilibria of the continuous version of the game.[20]

Hypothesis 1b *In the Bertrand case, increasing competition in the sense of switching from 2 to 4 players reduces investments.*

The next set of results concerns the effects of switching from Cournot to Bertrand competition.

Hypothesis 2a *For two-player games, increasing competition in the sense of switching from Cournot to Bertrand competition increases investments.*

Hypothesis 2b *For four-player games, increasing competition in the sense of switching from Cournot to Bertrand competition reduces investments.*

[20] For the discrete equilibria, competition has no effect.

We note that these last two predictions can be substantiated by using the equilibria of the discrete game as well as those of the continuous game. All predictions also hold both for the asymmetric pure-strategy equilibria and the symmetric mixed-strategy equilibria.

4.3 Details

The experimental sessions were conducted between November 2008 and February 2009 at the University of Zurich. The participants were undergraduate students.[21]

We implemented four sessions with Bertrand treatments, and four with Cournot treatments (see, Table 1). Two of the Bertrand and two of the Cournot sessions were two-player treatments. In each session there were 20 periods. No subject participated in more than one session. The four-player sessions had 36 players; the two-player sessions had 32 players each.[22] Sessions lasted about 90 minutes each.

At the end of each period, subjects were informed about the investment level and their own net payoff for that period. When the second stage was played out as well, they also learnt the price or the quantity decision of the other group member(s). In each session, participants received an initial endowment of CHF 35 (≈EUR 23). Average earnings including the endowment were CHF 36 (≈EUR 23) for the B2 one-stage session and CHF 32.13 (≈EUR 21) for the B4 one-stage session. For the Bertrand two-stage sessions the earnings were CHF 30 (≈EUR 20) for the two-player session and CHF 30 (≈EUR 20) for the four-player session. The amounts for the C2 and C4, one-stage sessions were CHF 49 (≈EUR 33) and CHF 39 (≈EUR 26), respectively. For the Cournot two-stage sessions the amounts were CHF 49 (≈EUR 32) for the two-player session and CHF 39 (≈EUR 26) for the four-player session. The experiment was programmed and conducted with the software z-Tree (Fischbacher, 2007) and subjects were recruited using ORSEE (Greiner, 2004).

[21] We did not exclude any disciplines. We had students of law, engineering, psychology, economics etc.

[22] In the four-player (two-player) treatments, we formed matching groups with eight (four) players each. Thus, we had a total of 52 matching groups.

5 Results

In this section, we present our experimental results. First, we provide a brief overview of the results in Section (5.1). Second, we look in detail at our hypotheses in Section (5.2).

5.1 Overview

Using matching group averages as independent observations,[23] Kruskal-Wallis tests reveal that we can reject the hypothesis that the investment levels of all treatments, of all one-, or of all two-stage treatments are drawn from the same population.[24] We explore the differences between the treatments in the following.

Figure 1 provides a first idea of how investments vary across treatments. Each panel contains the average per-period investments for the four cases of interest, distinguishing between the one-stage and the two-stage treatments. It also shows the equilibrium investments. Based on this descriptive evidence, we arrive at the following tentative conclusions.

1a. As predicted, increasing competition in the sense of increasing the number of players leads to lower average investments in the Cournot case.

1b. As predicted, increasing competition in the sense of increasing the number of players leads to lower average investments in the Bertrand case.

These results are supported by pairwise Mann-Whitney-U tests. We find significant differences between the C2 and C4 as well as between the B2 and B4 treatments.[25]

[23] In the following we always use matching groups as independent observations for the nonparametric tests.

[24] The null-hypothesis of no differences is rejected with a p-value of 0.000, if all treatments are considered. If we take only the one (two)-stage treatments into account the p-value is 0.006 (0.000)

[25] One-tailed tests reject the null hypothesis of no differences in average investments in favor of higher investment levels in C2 (B2) than in C4 (B4) at a p-value of 0.025 (0.048) for the one-stage treatments, and respectively at a p-value of 0.010 (0.003) for the two-stage treatments. Pooling the data of the one- and two-stage treatments results a p-value of 0.001 (0.000).

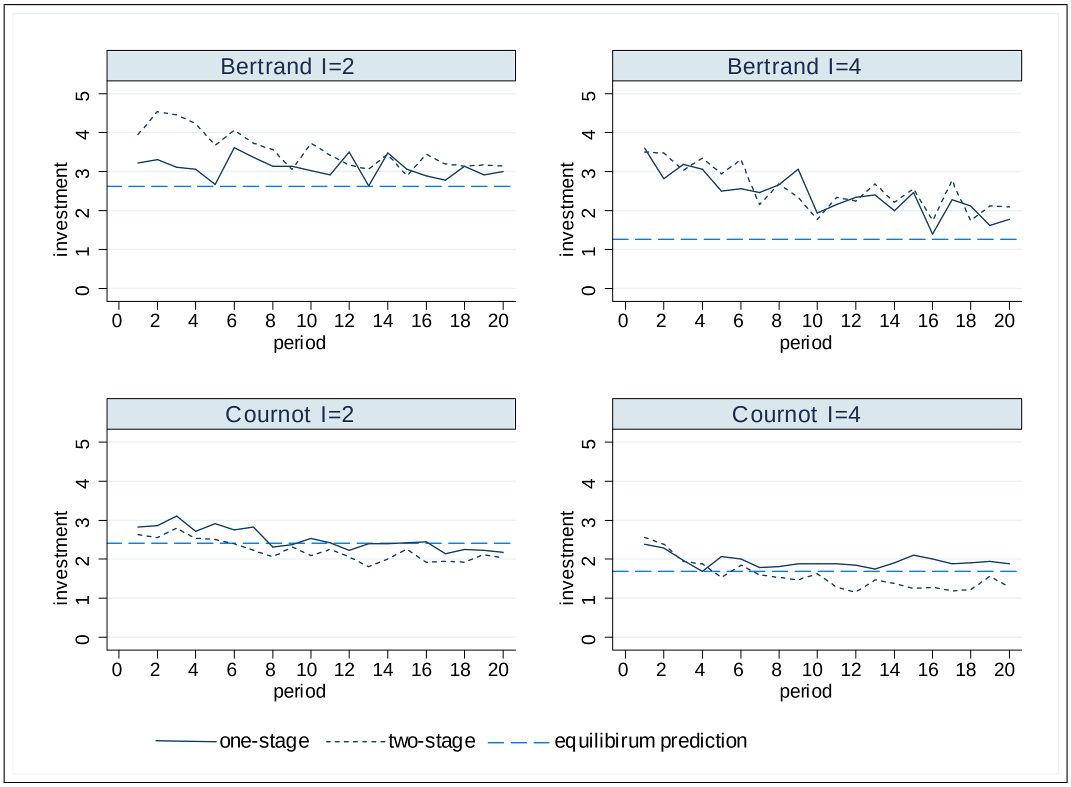

Figure 1: Average investment per period

2a. As predicted, increasing competition in the sense of moving from Cournot to Bertrand competition leads to greater average investments for the two-player treatments.[26]

2b. Contrary to the prediction, increasing competition in the sense of moving from Cournot to Bertrand competition leads to greater average investments for the four-player treatments.[27]

[26] This result is supported by a one-tailed Mann-Whitney-U test for the two-player one-stage (p=0.005) and two-stage treatments (p=0.000) and for the pooled data (p=0.000).

[27] A one-tailed Mann-Whitney-U test weakly rejects the hypothesis of no differences in investment levels between the two four-player treatments with a p-value of 0.100 for the one-stage and it rejects the null with a p-value of 0.014 for the two-stage treatments. The null-hypothesis of no difference is rejected with a p-value of 0.001 if we pool the data. However the mean ranks are always higher in B4 than in C4.

Hence, in terms of competition effects, there is one important deviation from the theoretical prediction: The effect of moving from Cournot to Bertrand competition is unambiguously positive.

Of course, we would also like to understand the sources of the deviation more clearly. Several additional observations are helpful in this respect.

3. The comparative statics results 1a-2b appear are similar for one-stage and two-stage treatments. Moreover, even the observed investment levels in the one-stage and two-stage treatments are quite similar. Two-tailed Mann-Whitney-U tests do not reject the null hypothesis of no differences in investment levels for the one- and two-stage four-player treatments (B4: $p=0.343$, C4: $p=0.200$). However, the hypothesis is weakly rejected for both two-player treatments (B2: $p=0.073$, C2: $p=0.077$).

The deviation from the theoretical prediction 2b arises in both treatment variants. It can therefore not result exclusively from subjects' considerations about possible deviations from equilibrium in the product market game.

Our next observation concerns the relation between investments and equilibrium predictions.

4. Whereas observed investments correspond to equilibrium predictions quite well in the Cournot treatments, there is substantial overinvestment in the Bertrand case in all treatments. In the C2 one-stage treatment we observe 4.75% overinvestment and 14.74% in the C4 treatment. However, in the two-stage treatments we observe 7.58% underinvestment in the C2 and 7.08% underinvestment in the C4 treatment. For the Bertrand treatments, we observe 18.21% overinvestment in the one-stage two-player treatment and 35.44% overinvestment in the two-stage case. For four players, we have 90.70% overinvestment in the one-stage treatment and 101.28% overinvestment in the two-stage treatment.

Understanding the sources of positive competition effects that are stronger than predicted thus essentially boils down to understanding why subjects choose above-equilibrium investments in the Bertrand case. Section 6 will therefore provide a more detailed analysis of these sources.

5.2 Comparative Statics

In the following, we provide a more careful statistical analysis, focusing on the comparative statics effects.

5.2.1 Number effects

We now investigate the number effects in more detail. First, we consider OLS models[28] of all Cournot treatments as well as of the one- and two-stage treatments separately. The model is given by

$$y_t^i = \beta_0 + \beta_1 \delta_{I4}^i + \beta_2 \delta_{P1-5}^i + \beta_3 \delta_{P6-10}^i + \beta_4 \delta_{P11-15}^i + \beta_5 \delta_{one-stage}^i + e_t^i, \quad (9)$$

where δ_{I4}^i is a dummy variable for intense competition (four players rather than two), and δ_{P1-5}^i, δ_{P6-10}^i, δ_{P11-15}^i are dummy variable for the first, second, and third quarter of periods. If we use the data of all treatments, we consider an additional dummy variable $\delta_{one-stage}^i$ which is equal to one for the one-stage treatments.

	(1) investment		(2) investment		(3) investment	
I4	-0.575***	(0.186)	-0.648***	(0.184)	-0.611***	(0.128)
P1-5	0.415**	(0.138)	0.682***	(0.149)	0.549***	(0.106)
P6-10	0.141	(0.103)	0.265***	(0.0675)	0.203***	(0.0635)
P11-15	0.0529	(0.0690)	0.0471	(0.0436)	0.0500	(0.0399)
one-stage					0.330**	(0.128)
constant	2.362***	(0.112)	1.970***	(0.106)	2.001***	(0.106)
N	1360		1360		2720	
R^2	0.082		0.113		0.113	

Standard errors in parentheses are corrected for matching group clusters.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 3: Number effects in the Cournot treatments

The first column in Table 3 deals only with the one-stage data. It shows that the estimated coefficient for β_1 is -0.575 and highly significant. If we consider only the two-stage Cournot treatments (Column (2)), we obtain a

[28] We correct the standard error for matching group clusters in all OLS models presented in the following.

highly significant β_1 of -0.648. The estimated effect is slightly lower than the predicted effect which is 0.71 both in one- and two-stage treatments. Using a t-test, we cannot reject the null-hypothesis of no difference between the two estimated coefficients ($t = 0.2790$). Thus, the comparative statics are essentially the same in one-stage and two-stage treatments. However, considering all treatments (Column (3)), we find a significant positive effect of being in a one-stage treatment. Thus, the level of investment is higher in the one-stage games. The time effects captured by the period dummies suggests that investments are higher initially than later on which holds independent of the data selection.

Summing up, we obtain the following confirmation of Hypothesis 1a.

Result 1a *For Cournot competition, investments are higher for two players than for four. Even though investment levels in one-stage and two-stage treatments differ, there is no significant difference in the size of the number effect across treatments.*

It is instructive to compare our results with the number effects obtained in standard Cournot output games. These games are structurally very similar to the one-stage version of the investment game, in that they also feature strategic substitutes and negative externalities.[29] Because of the latter property, players choose more output than under joint-profit maximization in the Nash equilibrium. Also, per-player output is decreasing in the number of players (as with investments in our case). Huck et al. (2004) show that this result is confirmed in the lab, but that it is less pronounced than theory would predict.[30]

We now move to number effects for Bertrand competition, corresponding to the two upper panels in Figure 1. The figures clearly suggest that investments are higher in the two-player game. We carry out the same OLS regressions as for the Cournot model (see Table 4).

The first column shows that the effect of the number of players has the predicted sign and is significant for the one-stage treatments. Considering

[29] The strategic substitutes property is standard for the output game. For the investment game, it follows from equation (2). Intuitively, as the competitor becomes more efficient, the other firm has lower demand and mark-up in equilibrium. Increasing own mark-up and demand by becoming more efficient is thus less attractive.

[30] Note, however, that Huck et al. consider a fixed-matching protocol which might foster collusion (lower outputs) in the two-player case.

the two-stage treatments in (Column (2)), we find a slightly stronger effect which is highly significant as well.[31] Running a t-test reveals that the difference between the two estimated coefficients is not significant ($t = 0.8865$). However the stage effect in Column (3) is weakly significant and negative. Again we find that investment levels are significantly higher in earlier periods.

	(1) investment		(2) investment		(3) investment	
I4	-0.675**	(0.293)	-0.992***	(0.205)	-0.834***	(0.179)
P1-5	0.626*	(0.313)	1.044***	(0.178)	0.835***	(0.178)
P6-10	0.491*	(0.275)	0.382**	(0.131)	0.437***	(0.150)
P11-15	0.294**	(0.0999)	0.135	(0.173)	0.215**	(0.0989)
one-stage					-0.302*	(0.176)
constant	2.744***	(0.161)	3.158***	(0.149)	3.102***	(0.171)
N	1360		1360		2720	
R^2	0.026		0.078		0.050	

Standard errors in parentheses are corrected for matching group clusters.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 4: Number effects in the Bertrand treatments

Summing up, we obtain the following confirmation of Hypothesis 1a.

Result 1b *For Bertrand competition, investments are higher for two players than for four. Even though investment levels in one-stage and two-stage treatments differ, there is no significant difference in the size of the number effect across treatments.*

5.2.2 Cournot vs. Bertrand

We now consider the effect of moving from comparatively soft Cournot to intense Bertrand competition. To repeat, the effect of such an increase is predicted to be positive for two players, but negative for four players. As reported earlier, comparison of the two left panels in Figure 1 suggests that the result for the two-player case is indeed borne out in the lab. Next, we consider OLS models of the one-stage and two-stage treatments separately and jointly. The model we estimate includes $\delta^i_{Bert\,\mathrm{rand}}$ as a dummy variable

[31] However, the effect is smaller than the predicted one, for which we obtain is $2.62 - 1.27 = 1.35$ using equation (3).

for intense (Bertrand) competition and, as before, dummy variables for the first, second, and third quarter of periods (δ^i_{P1-5}, δ^i_{P6-10}, δ^i_{P11-15}). $\delta^i_{one-stage}$ is a dummy variable for the one-stage treatment.

$$y^i_t = \beta_0 + \beta_1 \delta^i_{Bert\,\mathrm{rand}} + \beta_2 \delta^i_{P1-5} + \beta_3 \delta^i_{P6-10} + \beta_4 \delta^i_{P11-15} + \beta_5 \delta^i_{one-stage} + e^i_t. \quad (10)$$

	(1) investment		(2) investment		(3) investment	
Bertrand	0.583***	(0.170)	1.331***	(0.217)	0.957***	(0.150)
P1-5	0.386*	(0.199)	0.783***	(0.201)	0.585***	(0.144)
P6-10	0.311	(0.215)	0.317**	(0.123)	0.314**	(0.122)
P11-15	0.147**	(0.0674)	0.0333	(0.129)	0.0903	(0.0724)
one-stage					-0.0778	(0.150)
constant	2.303***	(0.138)	1.935***	(0.126)	2.158***	(0.127)
N	1440		1440		2880	
R^2	0.028		0.185		0.084	

Standard errors in parentheses are corrected for matching group clusters.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 5: Effects of the type of competition in two-player treatments

In all three models (Columns (1)-(3) in Table 5) the effect of competition on investment is positive and highly significant. In fact, the effect is much more pronounced than predicted.[32] Moreover, the effect is significantly different between one- and two-stage treatments ($t = 2.7135$). However, the stage dummy in model (3) is insignificant. The period dummies show that investments decrease significantly as time goes by, independent of the data selection.

Summing up, we obtain the following confirmation of Hypothesis 2a.

Result 2a *As predicted, mean investments are higher for the Bertrand game with two players than for the corresponding Cournot games, both in the one-stage and the two-stage treatments. The effect is even stronger than predicted and significantly different for one- and two-stage treatments.*

In the four-player case, the comparative statics prediction of Hypothesis 2b is not confirmed. The OLS results are shown in Table 6.

[32]The theoretical prediction is $\beta_1 = 2.62 - 2.4 = 0.22$.

	(1) investment		(2) investment		(3) investment	
Bertrand	0.483	(0.310)	0.986***	(0.172)	0.734***	(0.183)
P1-5	0.672*	(0.298)	0.953***	(0.122)	0.813***	(0.160)
P6-10	0.322	(0.227)	0.331***	(0.0757)	0.327**	(0.115)
P11-15	0.203	(0.128)	0.156	(0.123)	0.180*	(0.0859)
one-stage					0.117	(0.183)
constant	1.640***	(0.190)	1.210***	(0.142)	1.366***	(0.170)
N	1280		1280		2560	
R^2	0.030		0.088		0.056	

Standard errors in parentheses are corrected for matching group clusters.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 6: Effects of the type of competition in four-player treatments

Considering only one-stage treatments (Column (1)), we find no significant effect of stronger competition on investment, whereas we get a highly significant positive effect in the two-stage treatments (Column (2)) and in the pooled data (Column (3))[33]. Using a t-test we cannot reject the null-hypothesis of no difference of the effect of Bertrand vs. Cournot competition on investment in one- and two-stage treatments ($t = 1.4188$). Column (3) shows that there is no significant effect of the stage dummy on investment. Time effects are similar to the two-player case.

Summing up, we cannot confirm Hypothesis 2b.

Result 2b *Contrary to the prediction, investments are higher for the Bertrand game with four players than for the corresponding Cournot games. We find no significant difference in the effect between one- and two-stage treatments.*

All results presented above go in the same direction as the statements in Section 5.1.

6 Understanding Overinvestment

In the following, we try to improve the understanding of our comparative statics results. As the Cournot case essentially confirms the equilibrium

[33] The predicted effect is negative, 1.27-1.69=-0.42.

prediction,[34] the crucial question is what lies behind the clear overinvestment in the Bertrand case. To this end, we point to five pieces of evidence.

1. There is substantial overinvestment in the one-stage and two-stage treatments, but it is more pronounced in the latter case.
2. There are strong time effects.
3. There is substantial cross-player heterogeneity.
4. In the four player-treatments, players obtain negative profits on average in all periods, but the losses are decreasing over time. In the two-player treatments, average profits are mostly positive.
5. Compared to the mixed-strategy equilibrium, the overinvestment comes mainly from too low weight on low positive strategies rather than too low weight on zero.

Considering the question of overinvestment, we ran the following OLS regression model for all treatments:

$$\triangle y_t^i = y_t^i - y_t^{i*} = \beta_0 + e_t^i, \tag{11}$$

with y_t^{i*} standing for the predicted equilibrium investment. If subjects invest according to our prediction, the estimated constant β_0 should be zero. The results for all treatments are presented in Table 7 in the Appendix. We find that there is no significant over- or underinvestment in the Cournot treatments, whereas we find highly significant overinvestment in all two- and four-player Bertrand treatments. The overinvestment is higher in the two-stage and four-player treatments than in the one-stage and two-player treatments. These results support the descriptive evidence presented at the end of Section 5.1.

The second point has already been made in Section 5.2.

The third point is illustrated in Figure 2. This figure is a histogram of average per-player investments in the four Bertrand treatments. The heterogeneity across players is quite substantial. Figure 5 in the Appendix gives individual investment paths for the one-stage two-player treatment and shows that there also is a tremendous variety with respect to the stability of

[34] This is similar to Suetens (2005).

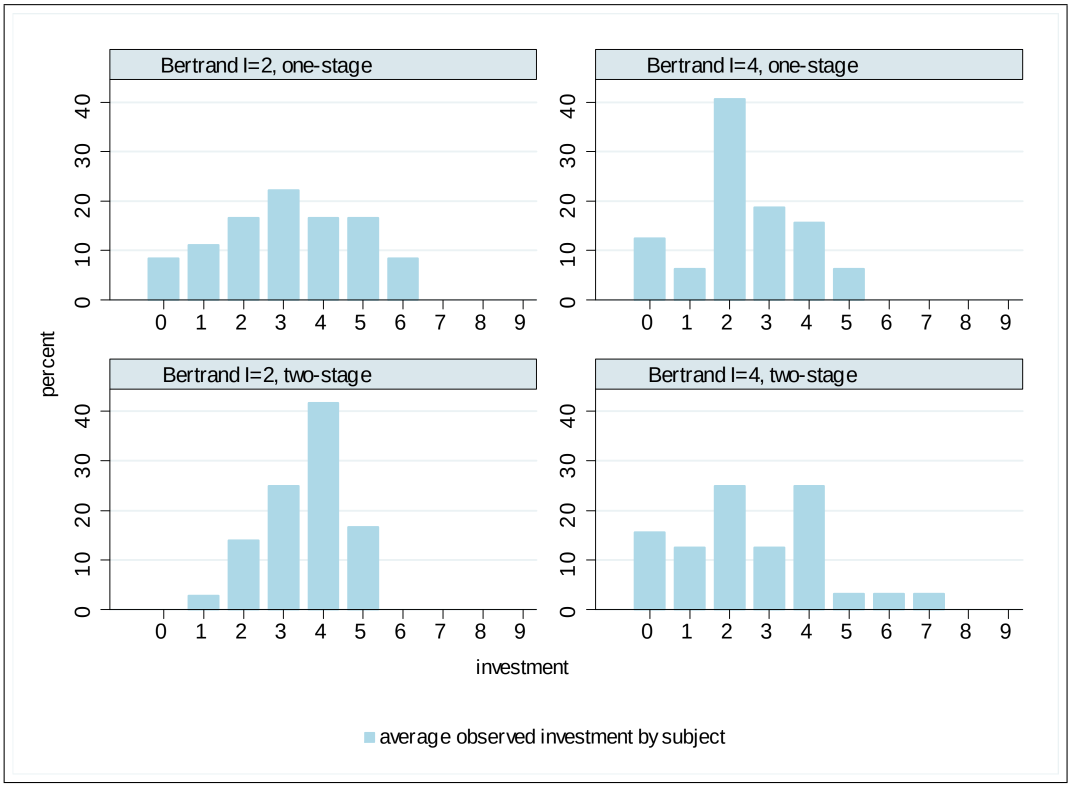

Figure 2: Average observed investment per subject for all four Bertrand treatments

individual behavior. A considerable fraction of the players had one or two preferred investment choices that were chosen at least half the time. Almost as many players hardly ever chose the same investment level twice in a row.

As to the fourth point, consider Figure 3, which shows how profits developed over times for the one- and two-stage case. The differences between the two-player and the four-player case are immediately evident. A two-tailed Mann-Whitney-U test rejects the null hypothesis of no differences between the one- and two-stage two-player treatments ($p = 0.000$), but the test cannot reject the null hypothesis in the four-player case ($p = 0.200$).

For the fifth point, consider Figure 4 in the Appendix. In all treatments, subjects choose 1 and 2 much less frequently than in the MSE. The differences for zero investments are much smaller, and in one case (B2, one-stage) there

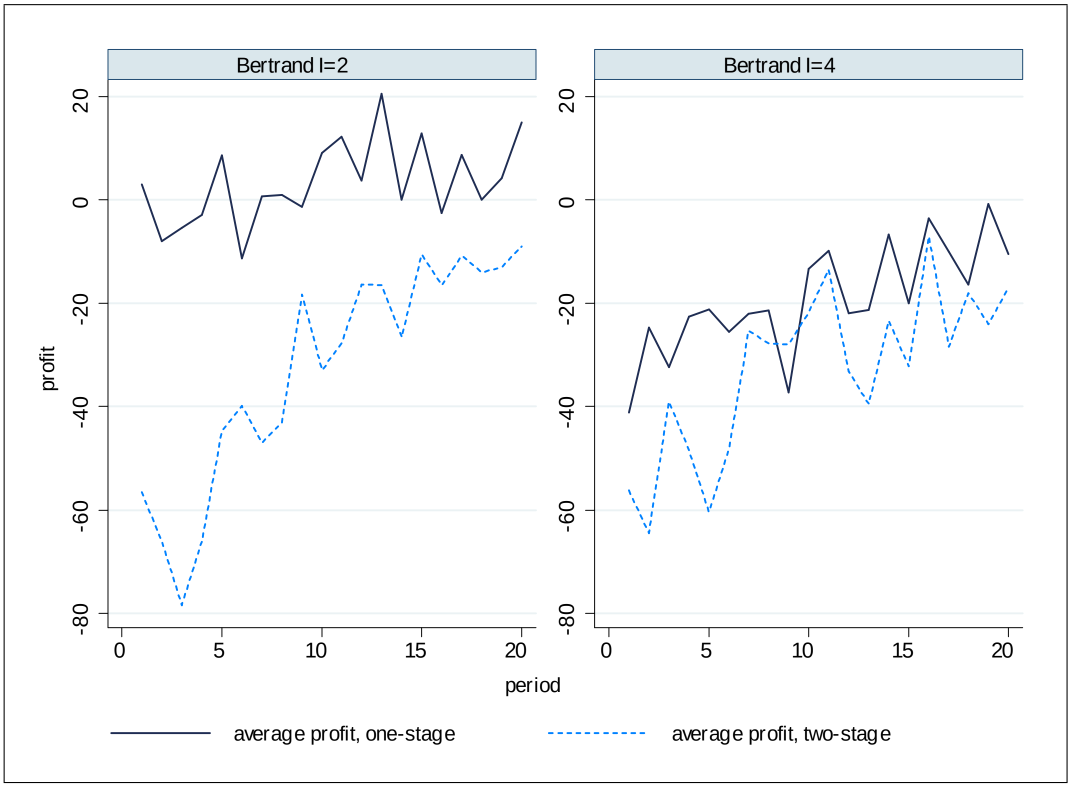

Figure 3: Average profits over time of all four Bertrand treatments

are more zero investments than predicted by the MSE.

Our observations suggest a number of possible explanations for the over-investment, all of which would apply both in the one-stage and the two-stage treatments.

1. *Joy of winning*: Subjects do not care exclusively about monetary payoffs, but derive an independent benefit from winning the game.

2. *Efficiency considerations*: Subjects deviate from equilibrium in order to come closer to joint-payoff maximization.[35]

3. *Reputation effects*: Subjects may have hoped to induce others to refrain from investing.

[35] See, e.g., Engelmann and Strobel (2004).

4. *Confusion*: Subjects were at least initially unaware of the high risk of making losses with high investment choices.

5. *Optimism*: Subjects were aware of the possible losses, but overestimated the chances that others would choose lower investments.

Given the heterogeneity of individual profiles, it seems unlikely that a single explanation applies to all players. The "joy of winning" effect, for instance, is consistent with the observation that subjects tend not to choose low investment levels if they invest at all. However, because of the substantial reductions in investments over time,[36] we can rule out that a "joy of winning" effect explains all observations. The joy of winning cannot explain why investments decrease over time.

Efficiency considerations are also not entirely convincing in the present setting. At least for $I = 4$, the deviations from equilibrium clearly reduce joint profits (which are zero in expectation in the mixed-strategy equilibrium). For $I = 2$, however, in most periods, average profits are positive, so that subjects indeed come closer to joint-profit maximization. Clearly, joint profit maximization arises in the asymmetric pure-strategy equilibria, but positive average profits can still be obtained for other asymmetric strategy profiles. One might argue that players are trying to coordinate on some outcome that is closer to joint-profit maximization, but fail to do so in the four-player case where it is obviously more difficult.

Among the three other explanations, the appeal of reputation effects as an explanation is of course limited by the fact that player identities were not common knowledge. The last two explanations are perhaps most compelling. The prevalence of high investments and negative profits in early periods is strong, which would appear to be consistent both with confusion and excessive optimism that fade away over time. Also, it is suggestive that these effects are stronger in the four-player case, where the strategic uncertainty is compounded by the fact that three opponents are present in each period. Finally, as Figure 4 shows, 10-15 % of the investments in all Bertrand treatments are weakly dominated strategies (6 or higher), also suggesting some degree of confusion.

Although we can rule out explanations of investment behavior that result *exclusively* from anticipated deviations in the two-stage game, we still have to

[36] See regression results in Section 5.2.2.

deal with the issue of why the comparative-statics effect is more pronounced in the two-stage case than in the one-stage case. This observation reflects two different components. First, the overinvestment in the Bertrand case is more pronounced for the two-stage treatments. Second, while there is a tendency towards overinvestment in the Cournot game for one-stage treatments, there is a tendency towards underinvestments in the two-stage treatments.

The underinvestment tendency in the two-stage Cournot treatments appears to have a plausible explanation. One effect towards underinvestment that is absent in the one-stage case is that, if subjects expect to collude on low outputs in the second stage, they will have less need for cost reductions. This is consistent with the observations: First, because of the underinvestment, average subgame equilibrium outputs corresponding to *actual* investment levels are lower than the subgame perfect equilibrium outputs. Second, average outputs across all two-stage Cournot treatments are even lower than those average subgame outputs.[37]

Perhaps the most plausible explanation of the more pronounced overinvestment in the two-stage Bertrand case is the greater strategic complexity. In the one-stage case, subjects should understand immediately from the payoff table that at most one player can make positive profits, which should deter investments. In the two-stage case, the value of an investment may be positive for both players, but this still requires very special second-stage actions, namely identical prices above equilibrium for all players. Subjects may be overestimating the chances that such coordination takes place. In fact, in the two-stage Bertrand treatments, subjects did not achieve such coordination in 98.75% of the markets for $I = 4$, and in 72.22% in the case $I = 2$.

7 Conclusion

This paper has analyzed the effects of more intense competition on investments in simple two-stage R&D models. In the first stage, firms whose marginal costs are identical ex-ante simultaneously invest in R&D. The investment leads to a decrease in marginal costs. In the second stage of the game, firms simultaneously choose quantities or prices in a homogeneous good market.

[37] For C2 (C4), average subgame equilibrium outputs are 10.74 (6.31) rather than 10.8 (6.34) as in the subgame perfect equilibrium. Average observed outputs are 10.11 (6.05).

When more intense competition is modeled as an increase of the number of firms for a given type of product market competition, the theoretical prediction is that, both for Cournot and for Bertrand competition, an increase in the number of agents yields lower mean investments. This hypothesis is confirmed in the lab. When more intense competition is modeled as a switch from Cournot to Bertrand competition, the observed investments increase, even though the mixed-strategy equilibrium only predicts this in the two-player case. An important limitation of our analysis concerns the very long run. As overinvestment tends to coincide with negative earnings in the Bertrand game, it is not sustainable. Thus, in the very long run, firms must either adapt their behavior or they will disappear from the market. This feature is much less pronounced in the Cournot game, where overinvestment is compatible with positive earnings. One might therefore conjecture that, in the long run, overinvestment disappears even in the Bertrand case.

8 Appendix

8.1 Tables

Cournot $I = 2$, $y_t^{i*} = 2.4$						
	(1) Δy_t^i		(2) Δy_t^i		(3) Δy_t^i	
β_0	0.114	(0.126)	-0.182	(0.135)	-0.0340	(0.0966)
N	720		720		1440	
Cournot $I = 4$, $y_t^{i*} = 1.69$						
	(1) Δy_t^i		(2) Δy_t^i		(3) Δy_t^i	
β_0	0.249	(0.154)	-0.120	(0.141)	0.0647	(0.119)
N	640		640		1280	
Bertrand $I = 2$, $y_t^{i*} = 2.62$						
	(1) Δy_t^i		(2) Δy_t^i		(3) Δy_t^i	
β_0	0.477***	(0.121)	0.929***	(0.177)	0.703***	(0.118)
N	720		720		1440	
Bertrand $I = 4$, $y_t^{i*} = 1.27$						
	(1) Δy_t^i		(2) Δy_t^i		(3) Δy_t^i	
β_0	1.152**	(0.297)	1.286***	(0.121)	1.219***	(0.151)
N	640		640		1280	

Standard errors in parentheses are corrected for matching group clusters.
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 7: Observed and predicted investment

In model (1) we use one-stage data, in model (2) two-stage, and in model (3) we pool one- and two-stage data.

8.2 Figures

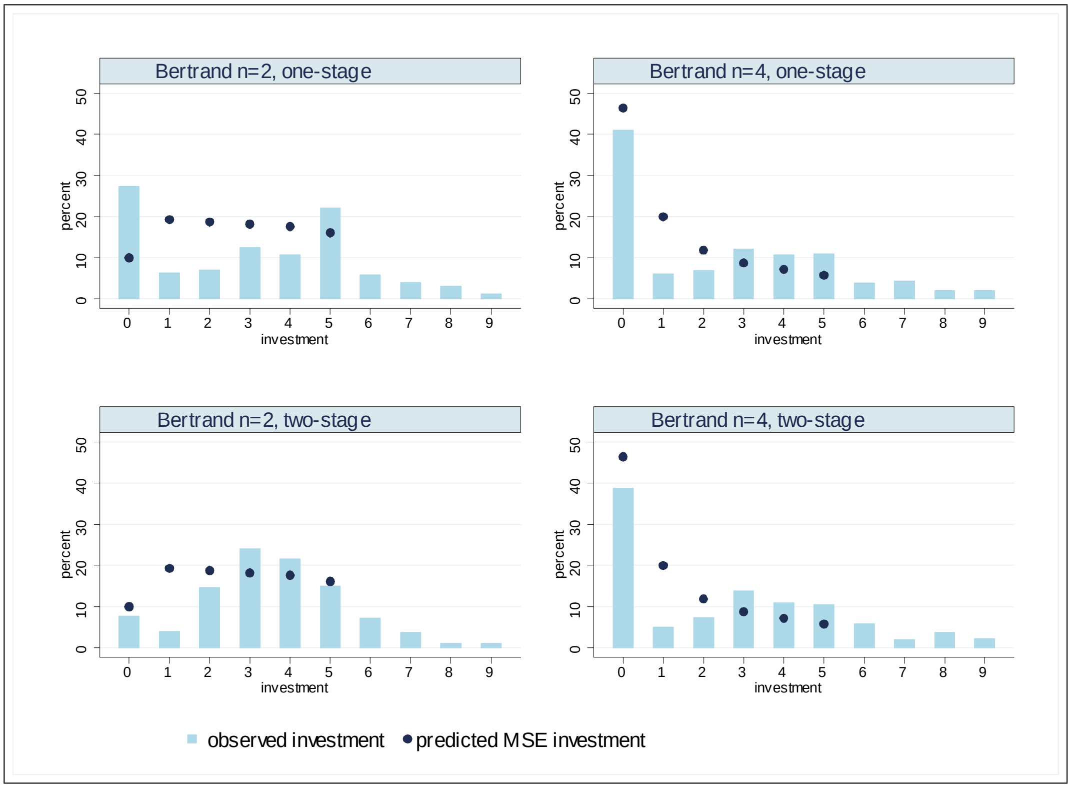

Figure 4: Observed investment levels in all Bertrand treatments and predicted MSE investment levels

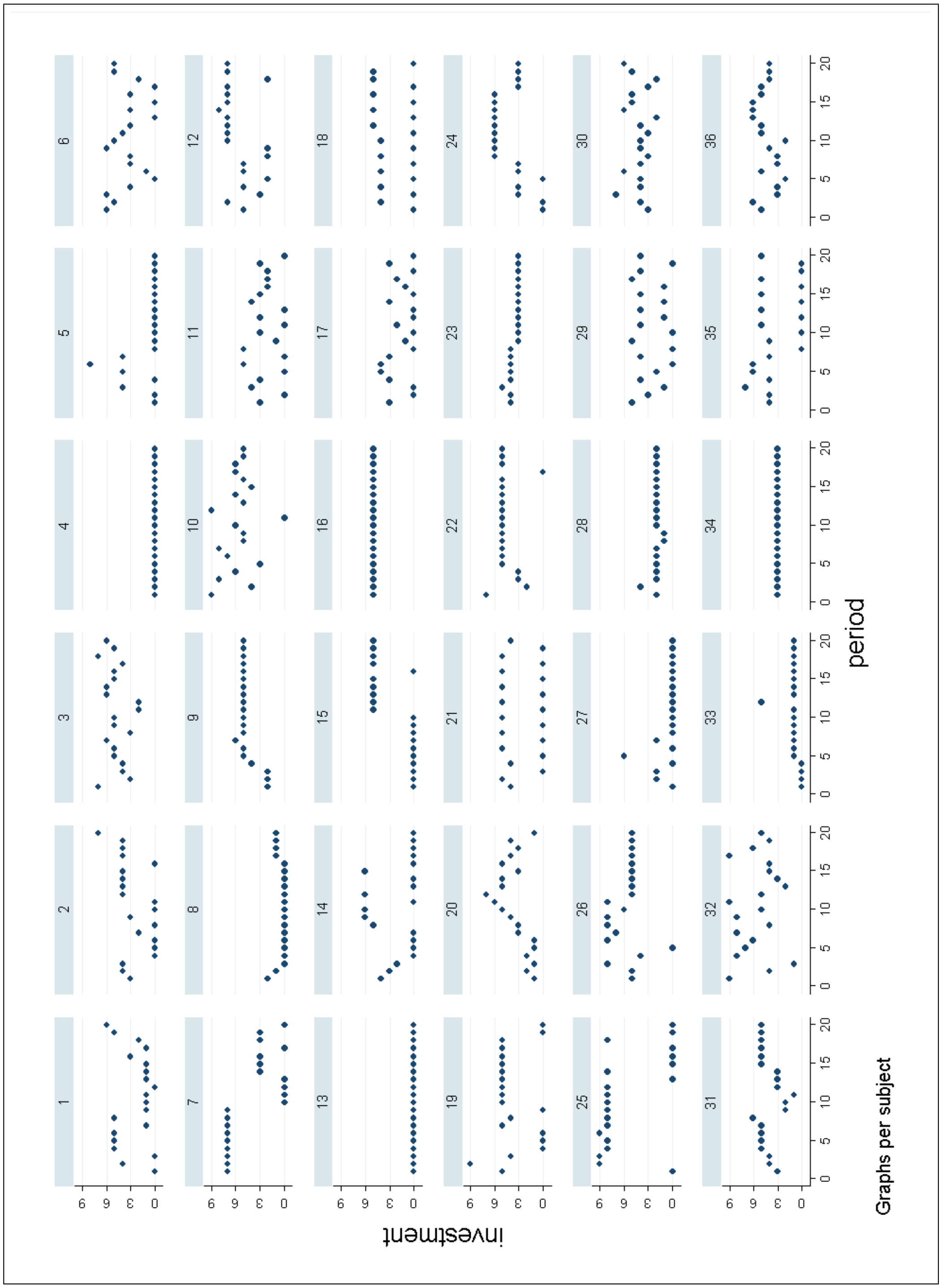

Figure 5: Investment per subject in the B2, one-stage treatment

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